

Degradation of alpine meadows exacerbated plant community succession and soil nutrient loss on the Qinghai-Xizang Plateau, China

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Abstract: In recent decades, global climate change and overgrazing have led to severe degradation of alpine meadows. Understanding the changes in soil characteristics and vegetation communities in alpine meadows with different degrees of degradation is helpful to reveal the mechanism of degradation process and take the remediation measures effectively. This study analyzed the changes in vegetation types and soil characteristics and their interrelationships under three degradation degrees, i.e., non-degradation (ND), moderate degradation (MD), and severe degradation (SD) in the alpine meadows of northeastern Qinghai-Xizang Plateau, China through the long-term observation. Results showed that the aggressive degradation changed the plant species, with the vegetation altering from leguminous and gramineous to forbs and harmful grasses. The Pielou evenness and Simpson index increased by 24.58% and 7.01%, respectively, the Shannon-Wiener index decreased by 17.52%, and the species richness index remained constant. Soil conductivity, soil organic matter, total potassium, available potassium, and porosity declined. However, the number of vegetation species increased in MD. Compared with ND, the plant diversity in MD enhanced by 8.33%, 8.69%, and 7.41% at family, genus, and species levels, respectively. In conclusion, changes in soil properties due to degradation can significantly influence the condition of above-ground vegetation. Plant diversity increases, which improves the structure of belowground network. These findings may contribute to designing better protection measures of alpine meadows against global climate change and overgrazing.

Keywords: alpine meadow; degradation; long-term observation; plant diversity; soil and vegetation characteristics

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1 Introduction

The Qinghai-Xizang Plateau, known as the "Water Tower of Asia", is a sensitive area of global climate change. It encompasses a diverse array of grassland types that play a crucial role in regional water cycle, ecological environment, and climatic regulation (Zhang et al., 2020; Wang et al., 2023a). Among these grassland types, alpine meadows constitute one of the primary categories on the Qinghai-Xizang Plateau, covering an area of approximately $97.68 \times 10^6 \text{ km}^2$ (Wang et al., 2023b). Alpine meadows have nurtured a rich variety of species and germplasm

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resources because of their unique geographical characteristics, such as high altitude and large temperature difference. Thus, alpine meadows have an important impact on maintaining ecosystem service functions such as climate regulation, water conservation, and soil formation and protection (Wang et al., 2023a). Owing to heavy industrialization (Nassauer and Raskin, 2014), global climate change (Wang et al., 2016; Anjali and Aditi, 2024), overgrazing (Gu et al., 2023), and irrational grassland management, the quality of grasslands has declined and ecological environments have been damaged (Bullard, 2012). Chinese government has applied a variety of measures, such as fencing, cutting turf, no-tillage reseeding, and fertilizer addition, to prevent grassland degradation (He et al., 2020; Chen et al., 2023). However, more than half of the meadows have been degraded to different degrees due to external disturbances and the effects of global climate change (Brierley et al., 2022).

The most significant variation of grassland degradation is a decline in vegetation cover and an increase in the soil bareness rate, followed by the loss of soil nutrients and change in the functional groups of vegetation (Zhao et al., 2024). Finally, the soil-vegetation equilibrium is disrupted. Soil nutrients support the normal growth of plants, whereas photosynthesis and other processes facilitate the exchange of compounds and energy transfer between vegetation and soil (Romio et al., 2022). This dynamic equilibrium between soil and vegetation is essential for maintaining the overall stability of grassland ecosystem. Therefore, it is of great significance to study the impacts of soil degradation on vegetation functional groups. In addition, some studies have reported the synergistic effects of vegetation degradation and soil degradation (Peng et al., 2020). Therefore, the fundamental purpose of managing degraded alpine meadows can be achieved by improving soil environment (Evanylo et al., 2016) and cultivating high-quality pasture grasses suitable to the area, for example, selecting and breeding pasture grasses with excellent traits and expanding seed bank (Zhang et al., 2023a). Additionally, it is necessary to investigate the changes in soil characteristics caused by severe grassland degradation, as well as the succession patterns of key and dominant plant species (Gao et al., 2019; Mao et al., 2020).

Degradation reduces grassland yield and quality, deteriorates soil, pollutes groundwater, and impedes ecological functions. Studies of the reparation of alpine meadows have focused on the increases in its grazing capacity, however, the long-term effects of grassland degradation on vegetation and soil characteristics are less concerned (Schneider et al., 2011; Shen et al., 2019; Zhang et al., 2023b). Therefore, the main purpose of this study is to reveal the relationships between grassland degradation and vegetation and soil changes in different degraded alpine meadows on the Qinghai-Xizang Plateau, China. The specific aims are (1) to obtain soil and vegetation changes during grassland degradation; (2) to reveal the evolution of dominant forage during grassland degradation; and (3) to analyze whether degradation degree changes the ability of alpine meadow to resist climate change. This study will help to understand the effects of alpine meadow degradation on vegetation and soil, further clarify the reparation of degraded grassland, and provide a reference for exogenous nutrient addition and vegetation improvement in alpine meadows.

2 Materials and methods

2.1 Study area

Study area is located in the Haibei Scientific Station, Northwest Plateau Research Institute, Menyuan Hui Autonomous County, Qinghai Province, China ($37^{\circ}36'48''\text{N}$; $101^{\circ}18'33''\text{E}$; 3200–3600 m a.s.l.). Study area has an obvious temperate continental climate and weak Southeast Asian summer monsoon. Restricted by high altitudes, the temperature is extremely low. Annual average temperature is -1.7°C , and precipitation is about 560 mm. Precipitation is mainly concentrated from May to September in plant growth season, accounting for about 80.00% of the annual precipitation (Zheng et al., 2013). Soil type is alpine meadow soil. For plant species in the study area, *Kobresia humilis* Serg. was the constructive species. *Elymus nutans* Griseb., *Stipa aliena* Keng, *Gentiana straminea* Maxim., and *Oxytropis kansuensis* Bunge were the dominant species.

2.2 Methods

Three types of degradation of alpine meadows in the study area were used, i.e., non-degradation (>90.00% average coverage; ND), moderate degradation (60.00%–90.00% average coverage; MD), and severe degradation (<60.00% average coverage; SD) (Fig. 1). Three sample plots were randomly selected in the study area, with three replicates per sample plot and a distance of about 100 m between the sample plots, totaling 9 sample plots and 27 soil samples. Soil samples about 2 kg were collected at a depth of 0–20 cm. All samples were collected in September 2023. In addition, this study evaluates the ability of alpine meadows to resist external disturbances based on the central role of vegetation and soil in the ecosystem. Vegetation functional group and soil characteristics status together reflect the health of alpine meadows and their ability to cope with changes in the external environment (Sun et al., 2022; Sadeghi et al., 2023).



Fig. 1 Overview map of non-degraded (ND; a), moderately degraded (MD; b), and severely degraded (SD; c) alpine meadows in the Haibei Scientific Station, Qinghai Province, China

2.2.1 Vegetation survey

Three replicated plots were randomly established, which are located within the degraded alpine meadows, with a distance of approximately 100 m between each plot. For each plot, quadrats with an area of 0.5 m² were set up in ND, MD, and SD to conduct the vegetation survey. Plant number, height, and coverage of each plant species were surveyed. We calculated importance value (IV) of plant species according to the means of relative abundance, height, and frequency of each species (Ma et al., 2022). The Shannon-Wiener index, Simpson index, species richness index, and Peilou evenness index were calculated (Yeom and Kim, 2011; Ma et al., 2022).

2.2.2 Soil sample collection and measurement

A soil auger (30 mm in diameter) was utilized to gather soil samples from a depth of 0–20 cm at each sample plot. Subsequently, three soil samples collected within each sample plot were mixed to ensure uniformity. Each composite soil sample was then air-dried and sieved through a 2-mm mesh to calculate soil physical-chemical properties. Methods of soil physical-chemical properties are shown in Table 1.

Table 1 Methods for measurement of soil physical-chemical characteristics

Index	Abbreviation	Measurement method	Reference
Soil total potassium	TK	Flame photometry	
Soil available potassium	AK	Ammonium acetate leaching-flame photometry	
Electrical conductivity	EC	Conductivity meter method	Bao, 2000
Soil porosity	SP	Ring knife method	
Soil organic matter	SOM	Potassium dichromate external heating method	

2.3 Data analysis

The Shannon-Wiener index (H'), Simpson index (D), species richness index (R), and Pielou evenness index (E) are used to assess plant diversity using the following equations (Nelson et al., 2005; Zhang et al., 2019; He et al., 2021):

$$H' = - \sum_{i=1}^n p_i \times \ln(p_i), \quad (1)$$

$$D = \sum_{i=1}^n p_i^2, \quad (2)$$

$$E = H'/H'_{\max}, \quad (3)$$

$$R = S, \quad (4)$$

$$IV = (\text{relative cover} + \text{relative density} + \text{relative plant height})/3, \quad (5)$$

where P_i is the proportion of individuals that belong to species i ; n is the number of the species; H'_{\max} is the maximum Shannon index; S is the total number of the species present; and IV is the important value of each species within the sampled area.

The data were analyzed using SPSS v.20.0 software. Significant differences in soil physical-chemical properties across different degradation levels were compared using one-way analysis of variation (ANOVA) followed by the least-square standard deviation test. Pearson's correlation analysis was employed to investigate the interaction between plant diversity index and soil environmental factors. Figures were plotted using Origin v.2022.

3 Results

3.1 Changes in vegetation composition

As degradation intensified, the types and IV of vegetation in alpine meadows notably changed. *E. nutans* emerged as the dominant species in ND and MD, accounting for 40.05% and 33.61%, respectively. However, the IV decreased by 6.44%, whereas that of *P. anserina* increased up to 28.55%. The subdominant species included *Medicago archiducis-nicolai* Sirj. (13.95%), *Lancea tibetica* Hook. f. et Thoms. (15.67%), and *E. nutans* (25.15%). The primary-associated, secondary-associated, and occasional species varied according to the degree of degradation (Table 2). Variations in plant height and cover degree structure led to competitive inhibition among certain dominant species due to taller cover degree of plants, resulting in slowdown or cessation of growth processes, thereby facilitating vegetation community succession.

MD and SD exhibited dominance at family, genus, and species levels in comparison with ND. At family level, the numbers were 9.09% and 18.18% higher in MD and SD than in ND, respectively (Fig. 2a); at genus level, they were 9.52% higher than that in ND (Fig. 2b); and at the species level, they were 8.00% and 4.00%, respectively (Fig. 2c). The IV of gramineous and leguminous plants decreased. Compared with ND, the IV for these groups decreased by 8.00% and 8.84% in MD, whereas they declined by 7.04% and 5.37% in SD, respectively. The IV of forbs increased by 16.84% and 12.41% in MD and SD, respectively, compared with ND. Harmful grasses were the highest in MD, followed by ND, and the lowest in SD (Fig. 2d). The differences observed across family, genus, and species levels reflect the inherent complexity of biodiversity and ecological adaptability. These variations were not only evident through morphological or physiological characteristics of distinct plant taxa but also influenced the structure and function of the ecosystem, serving as critical determinants of ecosystem stability.

3.2 Changes in vegetation diversity index

The Shannon-Wiener index in MD was greater and community species were more abundant, compared with ND; SD had the lowest species diversity (Fig. 3a). The Simpson index was the highest in MD, reflecting an uneven distribution of organisms among various species within the community; followed by SD and ND (Fig. 3b). The Pielou evenness index across all three degraded alpine meadows was directly proportional to the degree of degradation (Fig. 3c). Furthermore, the species richness index for MD exceeded those of ND and SD (Fig. 3d). These results demonstrate that grassland degradation significantly influences the diversity indices. The notable difference may primarily stem from shifts in the vegetation functional group attributes induced by grassland degradation. In contrast, the species richness index was relatively less

Table 2 Species and their important values (IV) of different degraded alpine meadows

No.	Species	Family	Life type	IV (%)		
				ND	MD	SD
S1	<i>Elymus nutans</i> Griseb.	Gramineae	P	40.05±2.4362 ^a	33.61±2.0526 ^b	25.15±1.0638 ^c
S2	<i>Medicago archiducis-nicolai</i> Sirj.	Leguminosae	P	13.95±1.8952 ^a	8.16±0.3524 ^b	4.99±0.6614 ^c
S3	<i>Potentilla anserina</i> Linn.	Rosaceae	P	7.54±0.5236 ^c	11.36±1.9931 ^b	28.55±3.5268 ^a
S4	<i>Potentilla saundersiana</i> Royle	Rosaceae	P	5.85±0.7455 ^a	4.68±0.3869 ^b	0.65±0.0142 ^c
S5	<i>Lancea tibetica</i> Hook. f. et Thoms.	Scrophulariaceae	P	5.46±0.4538 ^b	15.67±1.2514 ^a	5.51±0.6891 ^b
S6	<i>Oxytropis ochrocephala</i> Bunge	Leguminosae	P	4.71±0.3869 ^a	1.75±0.1417 ^b	0.72±0.0302 ^c
S7	<i>Saussurea nigrescens</i> Maxim.	Compositae	P	3.16±0.4258 ^a	1.07±0.1314 ^b	0.22±0.0624 ^c
S8	<i>Gentiana straminea</i> Maxim.	Gentianaceae	P	2.65±0.4736 ^a	0.62±0.0695 ^b	-
S9	<i>Koeleria litvinowii</i> Dom.	Gramineae	P	2.07±0.3847 ^a	0.98±0.0524 ^b	0.49±0.0625 ^c
S10	<i>Astragalus peterea</i> Tsai et YV	Leguminosae	P	1.93±0.1652 ^a	1.32±0.0589 ^b	0.22±0.0056 ^c
S11	<i>Aster farreri</i> W. W. Sm. et J.F. Jeffr.	Compositae	P	1.85±0.0769 ^b	5.37±0.1564 ^a	-
S12	<i>Angelica nitida</i> Wolff	Umbelliferae	P	1.58±0.1449	-	-
S13	<i>Gentiana macrophylla</i> Pall.	Gentianaceae	P	1.17±0.1864	-	-
S14	<i>Oxytropis kansuensis</i> Bunge	Leguminosae	P	1.11±0.0558 ^a	0.40±0.0146 ^b	-
S15	<i>Thalictrum rutifolium</i> Hook. f. et Thoms.	Ranunculaceae	P	1.02±0.0498	-	-
S16	<i>Allium cyaneum</i> Regel	Liliaceae	P	0.92±0.0089 ^a	0.65±0.0042 ^b	-
S17	<i>Thalictrum alpinum</i> Linn.	Ranunculaceae	P	0.91±0.0735	-	-
S18	<i>Gentianella azurea</i> (Bunge) Holub	Gentianaceae	A	0.71±0.1248 ^b	-	2.17±0.4561 ^a
S19	<i>Artemisia moorcroftiana</i> Wall. ex DC.	Compositae	P	0.64±0.0864	-	-
S20	<i>Ranunculus tanguticus</i> (Maxim.) Ovcz.	Ranunculaceae	P	0.57±0.0548 ^a	0.37±0.0423 ^b	0.08±0.0081 ^c
S21	<i>Euphrasia regelii</i> Wettst.	Scrophulariaceae	A	0.56±0.0039 ^b	-	0.66±0.0041 ^a
S22	<i>Microula sikkimensis</i> (Clarke) Hemsl.	Boraginaceae	P	0.52±0.0713 ^b	1.59±0.1347 ^a	-
S23	<i>Festuca sinensis</i> Keng	Gramineae	P	0.44±0.0059	-	-
S24	<i>Anemone rivularis</i> Buch.-Ham.	Ranunculaceae	P	0.37±0.0024	-	-
S25	<i>Tibetia himalaica</i> (Baker) Tsui	Leguminosae	P	0.26±0.0089 ^c	1.20±0.1489 ^b	1.49±0.1312 ^a
S26	<i>Saussurea pulchra</i> Lipsch.	Compositae	P	-	2.50±0.3337 ^b	5.57±0.7855 ^a
S27	<i>Anaphalis lactea</i> Maxim.	Compositae	P	-	2.20±0.0568	-
S28	<i>Erigeron acer</i> Linn.	Compositae	P	-	1.86±0.1004	-
S29	<i>Ajania tenuifolia</i> (Jacq.) Tzvel.	Compositae	P	-	1.24±0.6389 ^b	6.13±0.9184 ^a
S30	<i>Morina chinensis</i> (Bat.) Diels	Dipsacaceae	P	-	0.77±0.1832 ^b	1.31±0.3537 ^a
S31	<i>Ligularia sagitta</i> (Maxim.) Mattf.	Compositae	P	-	0.69±0.0518 ^b	4.21±0.4113 ^a
S32	<i>Gentianopsis paludosa</i> (Hook.f.) Ma	Gentianaceae	A	-	0.49±0.3737	-
S33	<i>Aconitum gymnanthrum</i> Maxim.	Ranunculaceae	A	-	0.49±0.0045 ^a	0.05±0.0001 ^b
S34	<i>Delphinium caeruleum</i> Jacq. ex Camb.	Ranunculaceae	P	-	0.44±0.0121	-
S35	<i>Astragalus polycladus</i> Bur. et Franch.	Leguminosae	P	-	0.29±0.0526 ^a	0.33±0.0051 ^a
S36	<i>Viola bulbosa</i> Maxim.	Violaceae	P	-	0.23±0.0109 ^b	0.89±0.0417 ^a
S37	<i>Stachys sieboldin</i> Miq.	Labiatae	P	-	-	3.30±0.2568
S38	<i>Polygonum sibiricum</i> Laxm.	Polygonaceae	A	-	-	2.59±0.1471
S39	<i>Taraxacum mongolicum</i> Hand.-Mazz.	Compositae	P	-	-	2.39±0.6627
S40	<i>Stipa penicillata</i> Hand.-Mazz.	Gramineae	P	-	-	1.17±0.0504
S41	<i>Festuca rubra</i> Linn.	Gramineae	P	-	-	0.73±0.0068
S42	<i>Cerastium pusillum</i> Seringe	Caryophyllaceae	P	-	-	0.43±0.0037

Note: ND, non-degraded; MD, moderately degraded; SD, severely degraded. S1–S42 indicate plant species. “-” indicates no value; P, perennial; A, annual; IV, importance value. Different lowercase letters within the same plant species indicate significant differences among different degraded alpine meadows at $P<0.050$ level.

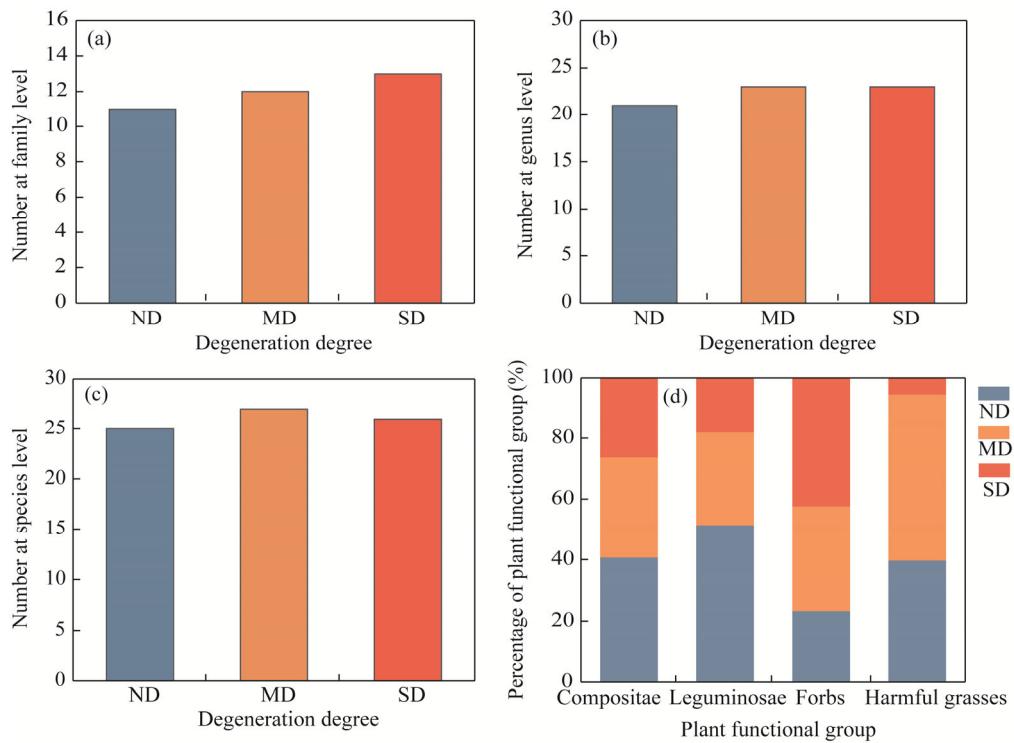


Fig. 2 Changes in vegetation characteristics of ND, MD, and SD alpine meadows. (a), number at family level; (b), number at genus level; (c), number at species level; (d), percentage of plant functional group.

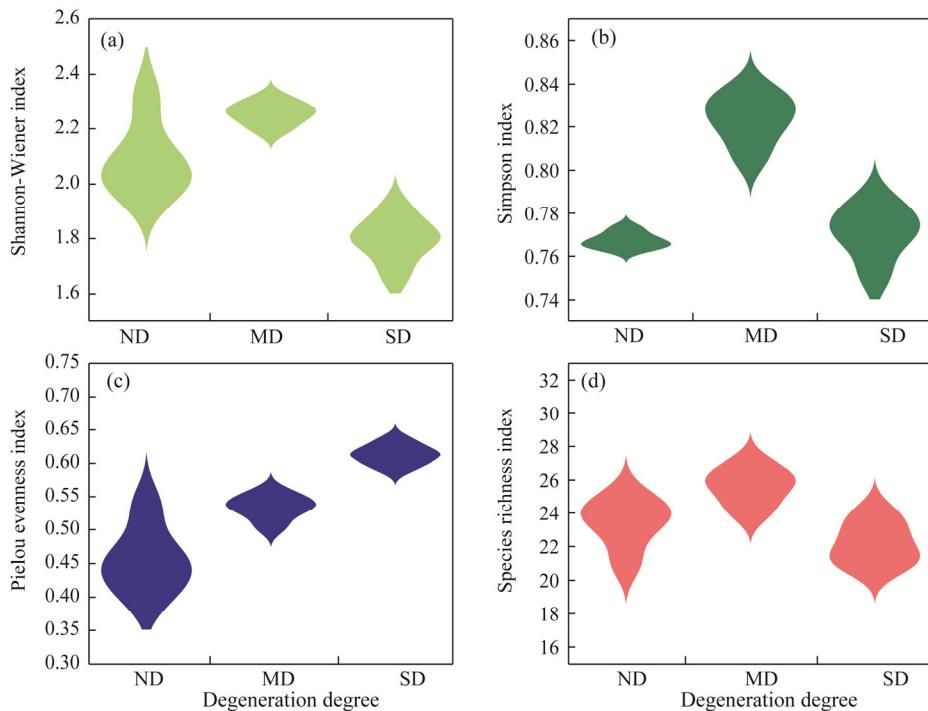


Fig. 3 Plant diversity indices of ND, MD, and SD alpine meadows. (a), Shannon-Wiener index; (b), Simpson index; (c), Pielou evenness index; (d), species richness index. In Figure 3, width indicates the density of data, and length indicates the range of variability.

affected, suggesting that although the composition of specific species may change in response to environmental alterations, overall biodiversity can remain relatively stable within certain limits. This observation underscores the complexity inherent in understanding the mechanisms by which grassland degradation impacts vegetation structure and function.

3.3 Changes in soil characteristics

As degradation of alpine meadows intensified, soil characteristics underwent continuous changes. Specifically, the electrical conductivity (EC), soil organic matter (SOM), total potassium (TK), and available potassium (AK) values significantly declined with the intensification of degradation of alpine meadows (Fig. 4a–d). Additionally, the soil porosity (SP) decreased but stabilized during the later stages of degradation (Fig. 4e). These findings indicate that as the degradation of alpine meadows intensifies, there is a corresponding decline in soil nutrient content, deterioration in aeration, alteration of the granular structure, and uneven distribution of nutrients. This result also revealed that at the macro-level, soil physical-chemical indicators were highly disproportionately distributed among ND, MD, and SD. Higher AK contents suggest a more balanced status. In contrast, contents for SOM and TK were significantly low. The variability of soil nutrients at the macro-level profoundly influenced the stability of soil ecosystem (Fig. 5). Even micro-changes of soil nutrients can trigger a chain reaction, such as altering the nutrient status of the soil, changing the growth environment of microorganisms, affecting their decomposition and regulation processes, and thus endangering the overall stability and health of soil ecosystem.

3.4 Correlation between soil and vegetation characteristics

Pearson's correlation analysis was performed to investigate the relationships between soil and vegetation characteristics (Fig. 6). The results showed significant positive correlations among all measured soil properties, indicating synergistic effects among different nutrient components. Conversely, negative correlations were observed between soil characteristics and species diversity indices. For example, the Pielou evenness index and Simpson index exhibited significantly negative correlations with SOM, EC, AK, SK, and SP. This result suggests that in alpine meadows, plant distribution is uneven, with fewer dominant species. The Shannon-Wiener index and species richness index were positively correlated with soil properties. Results indicate an interdependent and synergistic relationship among soil properties, where alterations in one index of soil can

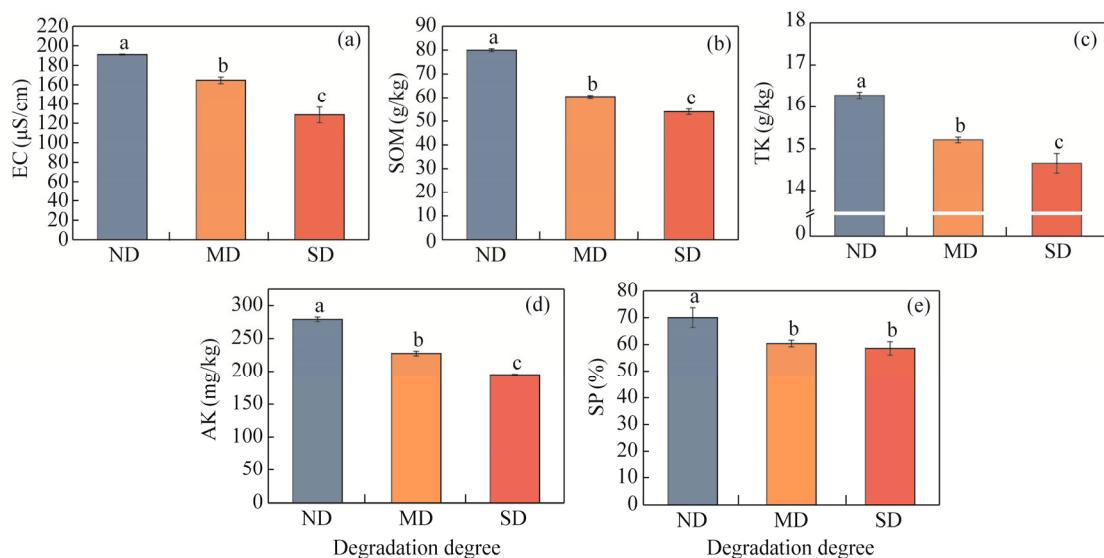


Fig. 4 Soil characteristics of ND, MD, and SD alpine meadows. (a), EC (electrical conductivity); (b), SOM (soil organic matter); (c), TK (total potassium); (d), AK (available potassium); (e), SP (soil porosity). Different lowercase letters indicate significant differences among different degraded alpine meadows at $P<0.050$ level. The abbreviations are the same in the following figures.

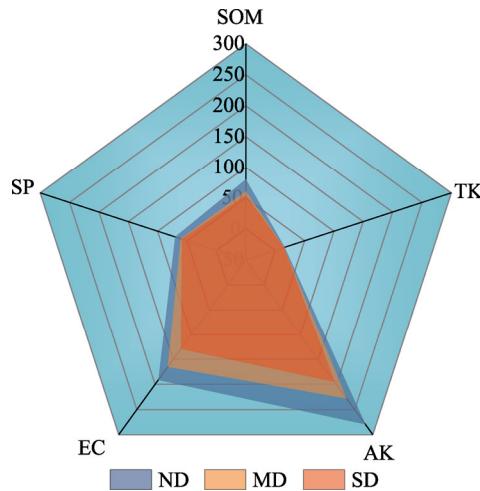


Fig. 5 Comparison of soil nutrient status in ND, MD, and SD alpine meadows. The values represent the relative distribution of the data in each dimension, and the overall approximation to a positive polygon represents a more balanced distribution of the soil nutrient status.

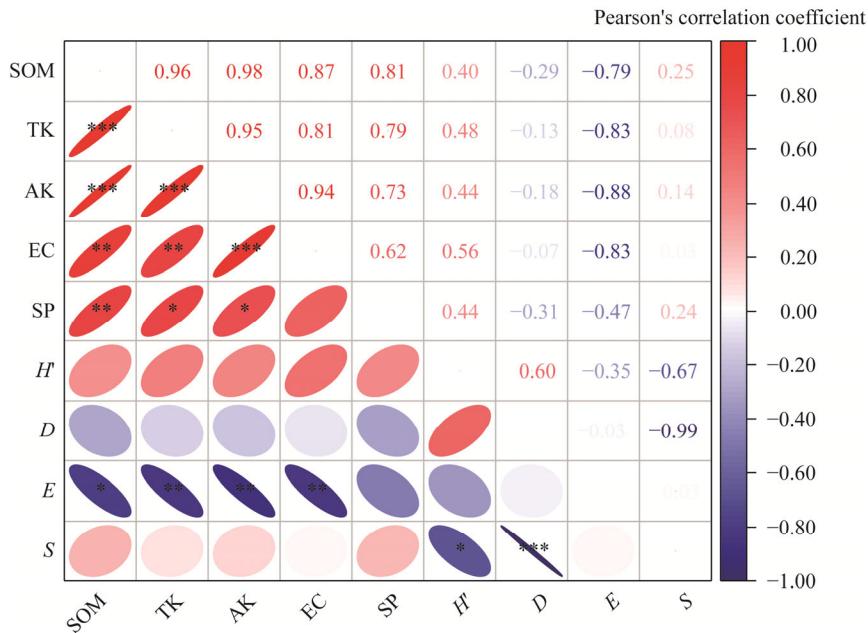


Fig. 6 Pearson's correlation coefficient between species diversity index and soil physical-chemical properties. H , Shannon-Wiener index; D , Simpson index; E , Pielou evenness index; S , species richness index. *, $P < 0.050$ level; **, $P < 0.010$ level; ***, $P < 0.001$ level.

markedly influence and cascade into others, thereby demonstrating complex interactions within the soil ecosystem. However, the intricacy of relationship between soil characteristics and vegetation diversity indices primarily arises from the fact that different types of vegetation possess varying requirements and preferences for specific soil attributes, leading to intricate soil-vegetation interactions.

4 Discussion

4.1 Effect of alpine meadow degradation on vegetation characteristics

Vegetation communities serve as indicators of grassland health. As degradation of alpine meadows progresses, these communities undergo varying degrees of succession. In ND, *E. nutans*

(IV=40.05%) from gramineae and *M. archiducis-nicolai* (IV=13.95%) from leguminosae were predominant (Table 2), suggesting the potential grazing utilization within this grassland ecosystem. Furthermore, leguminous grasses accounted for the largest proportion in ND (Fig. 2b), which helped to maintain the nitrogen balance in grassland ecosystems. Many leguminous grasses harbor and interact with rhizobacterium in their root systems that form nodules for nitrogen fixation (Roy et al., 2020). This process effectively captures atmospheric N and positively influences nitrogen cycling and deposition within ecosystems (Britton et al., 2019). This positive feedback loop promoted the plant growth of gramineae and leguminosae.

In MD, the proportions of gramineae and leguminosae decreased, whereas those of harmful grasses and forbs increased, which formed the highest plant species. The potential reasons of this result are as follows: (1) decreased soil fertility due to soil degradation affected the growth and development of gramineae and leguminosae plants, because these plants usually require high soil nutrients (Chippano et al., 2021), resulting the decreases in their numbers; (2) harmful grasses and forbs usually exhibit fast growth and strong adaptability (Wang et al., 2020) and can survive and reproduce under harsh environmental conditions, dominating the habitats where gramineae and leguminosae might grow; and (3) the potential function of MD cannot be neglected although MD had lower grazing utilization than ND (Pubudu et al., 2021). For example, many harmful grasses and forbs have extensive canopies and well-developed root systems (Hu et al., 2018), which protect alpine meadows from rain-induced erosion and inhibit the expansion black soil areas (Dong et al., 2013). In addition, lower grazing utilization means there will be less disturbance from livestock, further enhancing the potential natural resilience of MD to a certain extent (Li et al., 2022b; Mari et al., 2023).

In contrast, SD had the most forbs and the least harmful grasses. This result is due to the low vegetation cover and bare soil in SD, giving forbs the competitive advantage and increasing its populations. Certain forbs may act as pioneer species capable of rapidly colonizing bare soil surfaces (Hekkala et al., 2014), preventing erosion and creating favorable growing conditions for subsequent plant communities. Additionally, certain forbs, such as *L. sagitta* and *P. sibiricum* possess significant medicinal value along with robust resistance against low temperatures, droughts, and salinity levels. These forbs have also adapted to the ecological environment of SD and play a crucial role in maintaining the ecosystem stability and balance (Sun et al., 2023).

4.2 Effect of alpine meadow degradation on soil characteristics

Soil characteristic plays an important role in the soil-vegetation system and is a dominant factor affecting plant growth. Soil deterioration is the primary driver of alpine meadow degradation, which stems from substantial changes in the physical-chemical properties (Li et al., 2019). Regarding soil physical properties, we found that increased soil degradation greatly changed soil physical properties, with both soil EC and SP showing a decreasing trend. First, the changes in soil granular structure, probably due to anthropogenic disturbances and severe trampling by livestock, led to decreased porosity (Bethany et al., 2019). Second, degradation can result in the succession of aboveground vegetation communities and inhibit the growth of plants with root systems containing high levels of salts and ions, thus affecting soil EC (Li et al., 2024). These changes not only reshape the overall structure of soil and inhibit soil respiration rates, they also affect atmospheric carbon dioxide (CO_2) levels and carbon accumulation rates of soil (Wang et al., 2017).

Soil nutrients are crucial for the normal growth of above-ground vegetation. This study reported that increased degradation significantly reduced SOM, TK, and AK contents. This decline can be attributed to the fact that a portion of SOM originates from plant residues (Shannon et al., 2022). Consequently, the degradation of surface vegetation can markedly decreased vegetation cover, subsequently reducing the amount of SOM generated through soil decomposition. Furthermore, degradation increased the risk of soil erosion, leading to substantial losses of SOM due to both wind and water erosions. Additionally, it is possible that alkaline soils within the study area may have accelerated SOM loss (Chen et al., 2024). The decrease in TK and AK contents can be linked to degradation processes that promote an increase in forbs and harmful

grasses due to their high potassium uptake (Zeng et al., 2024). This phenomenon disrupted the morphological transformation of K and hindered with cross-border signal regulation (Fan et al., 2022), ultimately resulting in diminished TK and AK contents. More critically, global climate change is altering plant root morphology while reducing areas associated with inter-root nutrient uptake (Liang et al., 2014; Li et al., 2022a). Over time, this disruption will affect the dynamic balance among soil-microbe-plant systems, leading to decreased soil nutrient content and ongoing shifts within vegetation functional groups.

To sum up, grassland restoration efforts should prioritize two objectives: vegetation restoration and soil quality improvement. When developing restoration strategies, it is essential to consider multiple factors, such as climatic conditions, rodent infestations, and overgrazing, to ensure that proposed solutions are scientifically sound, feasible, and environmentally sustainable (Olofsson et al., 2012; Yuan et al., 2023). This integrated approach aims to restore soil health while promoting vegetation diversity, thereby effectively mitigating and reversing the degradation of grassland ecosystems.

4.3 Strategies to deal with alpine meadow degradation

The degradation of alpine meadows can lead to severe ecological deterioration and sudden declines in biodiversity. In the context of addressing climate change and overgrazing, it is essential to focus on the complex interactions between internal and external environments in alpine meadows and seek external interventions to combat degeneration. For soil characteristics, excessive reliance on fertilizers should be avoided. Alpine meadow soils are rich in nutrients, including roots, soil microorganisms, and unactivated nutrients (Borchard et al., 2012; Anna et al., 2015). Therefore, during restoration, incorporating beneficial microorganisms may be considered an effective strategy to activate these nutrients through microbial metabolic activities and synergistic interactions with root-associated microorganisms, thereby enabling plant uptake and reducing the need for exogenous fertilizers (Rane et al., 2022). Moreover, maintaining favorable vegetation conditions is crucial for mitigating degradation. However, this suggestion does not necessarily imply a high degree of uniformity among vegetation types. Different species exhibit varying levels of resistance to cold temperatures, drought, and human disturbances (Feng et al., 2024), contributing to ecosystem stability. Moreover, diversity of vegetation helped to prevent irreversible degradation resulting from rapid succession, which can be caused by factors such as global climate change and severe disturbances (Ma et al., 2019; Shao et al., 2024).

4.4 Limitation and implication

Alpine meadow degradation is a dynamic process that involves in many factors (Brierley et al., 2022). In this study, we commenced our investigation from three different levels of degradation, i.e., ND, MD, and SD. Our objective was to more accurately elucidate their degradation characteristics, thereby facilitating the formulation of targeted restoration measures. Furthermore, this study advocates for the introduction of appropriate grass species within alpine meadows to effectively mitigate ecological deterioration caused by degradation through the promotion of vegetation diversity (Strömborg and Staver, 2022).

It is important to note that changes in vegetation characteristics and soil nutrient status resulting from alpine meadow degradation are critical for future restoration and management efforts in the area. However, this study only monitored vegetation and soil data from selected alpine meadows on the Qinghai-Xizang Plateau over a one-year period. Thus, it is difficult to comprehensively and systematically reveal the dynamic change characteristics of alpine meadow degradation. Therefore, future research should concentrate on temporal and spatial heterogeneity by extending study durations and expand geographical coverage to gain deeper insights into the mechanisms underlying alpine meadow degradation (Hu et al., 2024). Additionally, climate change and external disturbances are key factors driving this degradation process (Brierley et al., 2022). This study did not incorporate variables such as precipitation, temperature, or grazing pressure. Consequently, its findings may be limited in completeness and applicability, and subsequent research should comprehensively consider these factors.

5 Conclusions

The degradation of alpine meadows is a complex process that is regulated by various factors, and the restoration of these ecosystems is time-consuming and more challenging. As the degradation intensified, the species richness gradually stabilized; however, the community structure changed significantly, especially decreasing the presence of gramineae and leguminosae as well as increasing those of forbs and harmful grasses. In addition, the deterioration of soil aeration properties and a significant decline in nutrient content led to the succession of dominant species in the ecosystem. In conclusion, the restoration of alpine meadows in the context of global climate change requires a primary focus on maintaining and optimizing the balance of the soil-vegetation system. This study emphasizes that the key is to improve the resilience of the ecosystem to external disturbances and changes, rather than pursuing excessive grazing utilization.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

Conceptualization: LI Shuangxiong, YAO Tuo; Methodology: LI Shuangxiong, LEI Yang; Formal analysis: LI Shuangxiong, CHAI Jiali; Writing - original draft preparation: LI Shuangxiong; Writing - review and editing: LI Shuangxiong, YAO Tuo, LI Changning; Funding acquisition: YAO Tuo. All authors approved the manuscript.

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